Ife Journal of Technology, Vol. 20(1), 58-67, 2011

Full Paper

EROSION CORROSION IN THE OIL AND GAS INDUSTRY: A REVIEW

O.O. Ige
Department of Materials Science and Engineering
Obafemi Awolowo University
Ile –Ife, Nigeria

L.E. Umoru
Department of Materials Science and Engineering
Obafemi Awolowo University
Ile –Ife, Nigeria

O.E. Olorunniwo
Department of Materials Science and Engineering
Obafemi Awolowo University
Ile –Ife, Nigeria

M.O. Adeoye
Department of Materials Science and Engineering
Obafemi Awolowo University
Ile –Ife, Nigeria

ABSTRACT

This paper reviews the various factors that affect erosion corrosion in the oil and gas industry. The mechanisms are highlighted and explained, with a view to understanding the underlying principle of the degradation phenomena. There are many monitoring techniques that are used in evaluating erosion corrosion but three are commonly employed in the laboratories. The benefits and limitations associated with these methods - rotated disc, rotated cylinder and jet impingement are reviewed. Erosion corrosion is regarded as a surface process that can be controlled via surface engineering for example, using coatings and inhibitors coupled with materials selection. Some of the critical parameters, such as inhibitor concentration as a function of flow parameters are discussed.

Keywords: *Erosion corrosion, corrosion monitoring, inhibitor, corrosion resistant alloys*

1. INTRODUCTION

The oil and gas industry exposes a variety of materials to corrosive fluids, often containing solids such as sand. The combination of a corrosive environment, high fluid velocity, and entrained solids typically lead to the loss of material from the surfaces in contact with the flowing hydrocarbon fluid. Sweet corrosion in carbon steel pipelines carrying oil-water mixtures has long been a problem in the oil industry. Corrosion - related problems in oil-gas production and processing operations result in loss of millions of dollars each year in downtime, lost production and damaged pipelines (Evans et al., 2004). With the use of enhanced oil recovery techniques, CO_2 corrosion in oil-water pipelines has become common causing much concern in transportation of these multiphase fluids over long distances from remote wells to separation sites (Evans et al., 2004; Vuppu and Jepson, 1994).

In the oil and gas industry, it has been discovered that there is continuous growing demand in energy consumption and also that convectional energy sources are depleting at a fast rate. Then new sources such as oil sands are expected to be increasingly relied upon to make the difference in future global oil and gas production. The most energy – and cost–efficient manner to transport oil sands from excavation to the excavation plant is by using a hydrotransport system. In the hydrotransport process, oil, sand and water are mixed together to make a slurry and this is transported via pipeline (Tian and Cheng, 2008). This multiphase system will definitely lead to some degradation mechanism.

The effect of flowing liquid streams on the degradation of engineering components is of great importance in many industrial processes. Flow induced corrosion is often used to describe the accentuation of corrosion resistance when mass transfer of reactants and products is enhanced. They are described according to their appearances and causes, which are brought about by the flow mechanisms of the system, when the mechanical forces of the flowing fluid prevail at the metal/environment interface then erosion corrosion and cavitation corrosion occur (Hu and Neville, 2002). Flow induced corrosion is defined as a process whereby the corrosion rate of a material is increased in a moving fluid. The effects of flow velocity on flow induced corrosion have been categorized into three, namely; low, medium, and high velocities regimes of erosion corrosion (Neville and Hu, 2001).

Typically, corrosion research is conducted in static solutions. Hydrodynamic factors are often ignored in the analysis of corrosion kinetics, or at best a hydrodynamic regime is used that does not effectively simulate the industrial environment of interest (Wharton and Wood, 2004). One significant contributing factor in the degradation of pipeline in oil and gas production is erosion-corrosion. It is seen that the contributions of corrosion and erosion to erosion-corrosion rate rank approximately 30% and 70%, respectively (Wang et al., 2005; Tian and Cheng, 2008). Erosion-corrosion is a degradation phenomenon that falls into a broad category of tribo-corrosion processes, which includes, for example, abrasion, corrosion and cavitation corrosion. These are not specific forms of corrosion but are degradation processes that involve the action of a mechanical process (for example, the impact of a solid particle) in conjunction with an electrochemical corrosion process. The material loss mechanism is caused by flowing fluid (containing or free from solid particles) disrupting or thinning the protective film of the corrosion product (Reyes and Neville, 2001; Neville et al., 2003; Dave et al., 2008; Fan et al., 2011).

Industries like chemical, material processing, pump manufacture, offshore and marine technologies, mining, metallurgical, oil and gas among others experience considerable deterioration processes as a result of erosion-corrosion (Wood and Hutton, 1990; Heitz, 1996; Stack and Paungwiwat, 2002; Chen et al., 2003; Wood and Speyer, 2004; Xu and Zhuo, 2010). Some of the equipment affected are pumps, impellers, valves, heat exchanger tubes, tees and elbows in pipework, manifolds, inspection omegas, agitators and so on (Wood and Hutton, 1990; Heitz, 1996; Neville and Dougal, 2002;

Chen et al., 2003; Hernandez-Rodriguez et al., 2007; Mohammed, 2010). Generally, the economic and effective operation of machinery and plant involved in fluids handling is increasingly dependent on the utilization of materials that combine high corrosion resistance and good wear resistance. The synergistic effect between erosion and corrosion is significant and is dependent on the material (Heitz, 1996). In multiphase systems the effect of each constituent needs to be defined and clearly understood. This review highlights these and the various factors that have profound effects on the erosion corrosion mechanism in the oil and gas industry.

1.1. Sand Management

Sand production is a common problem in oil and gas production and this may cause considerable erosion damage in critical parts of the transport and processing equipment leading to expensive failures and loss of production time (McLaury et al., 1999; Shirazi et al., 1999; Mohammed, 2010). The mechanical influence, frequency and extent of impacts by sand or other impacting species can cause the material to make a transition into a regime where active and passive sites are constantly forming on one surface (Aracic et al., 2010). It has been established that erosion rate is proportional to sand production rate as well as other factors like fluid properties, flow regime, pipe material properties and sand characteristics (Shirazi et al., 2000).

1.2. Oil and Sand

Concerted efforts are being deployed by industry to enhance the rate of oil and gas recovery to meet the global demand for energy. The mining of oil sand and the shift towards subsea developments, particularly associated with deep well production, horizontal drilling and the use of hydrotransport systems where oil, sand and water are mixed together (slurry), increases the risk of material degradation by erosion corrosion. Slurry erosion corrosion is regarded as a major problem in the oil and gas industry (Stack and Paungwiwat, 2002; Nesic et al., 2008; Neville and Wang, 2009). The presence of some active substances such as fine particles of sand, dissolved salts, CO_2, H_2S, bacterial activity and in some cases even the presence of oxygen aggravates corrosion in formation water. Crude oil also contains an important quantity of highly mineralized water, rich gases with a large percentage of CO_2, and sand grains from the petroliferous bed (Ripeanu et al., 2007)· From the corrosion standpoint, CO_2 corrosion is one of the most important problems in the oil and gas industry (Cabrini et al., 1998; Wood, 2006).

1.3. Carbon Dioxide Corrosion

It is believed that one significant factor of pipelines in oil and gas production is CO2 corrosion. In carbon steel piping systems handling fluids containing water and dissolved CO2 under a range of conditions, and FeCO3 (iron carbonate) scale can form on the pipe wall and provide a measure of protection against CO2 corrosion. If the fluid also contains sand, particles of sand impinging the pipe wall can remove the protective scale or prevent it from adhering to the wall. Without the scale to protect the pipe, CO2 corrosion can progress at an accelerated rate (Shadley et al., 1996). Due to greater solubility of the precipitable corrosion products, the presence of CO2 therefore lowers the flow rate thresholds corresponding to the appearance of erosion-corrosion phenomena. Indeed, the pronounced erosion corrosion often observed in CO2 fields has led to confusion between CO2 corrosion and erosion-corrosion. With or without CO2, erosion-corrosion attack has unmistakable characteristic features (Houghton and Westermark, 1983; Crolet and Boris, 1991). The presence of solids is known to induce erosion and its interaction with corrosion is poorly understood in CO2 environments. The mechanism of CO2 is still considered to be a grey area despite the volume of work that has been carried out. The effect of fluid dynamics on this type of corrosion needs to be determined and some of the parameters are flow velocity, flow regimes and the effect of liquid shear stress at the pipe wall (Hu and Neville, 2008).

1.4. Flow Induced Corrosion

The effect of flow on CO_2 corrosion has been the subject of a large number of investigations. The studies can be grouped into four main topics (Figure 1): i) effect of mass transfer; ii) effect of flow on removal of corrosion products; iii) effect on corrosion inhibition; and iv) effect on erosion and erosion-corrosion. It was shown that erosion corrosion causing flow-induced localized materials attack is mainly found under conditions when the material is covered with protective layers. Local destruction of such layers by fluid dynamic forces is the primary reason (Gulbrandsen, 2005; Schmitt and Bakalli, 2008).

1.5. Erosion corrosion

Erosion is defined as the removal of material from a solid surface by the repeated application of mechanical forces. These forces are induced by solid particles, liquid droplets, or cavitation. Erosion may be attributed to removal of the metal, the inhibited film, and/or protective corrosion scales. In a recent survey, erosion-corrosion was rated in the top five most prevalent forms of corrosion damage in the oil and gas industry (Cabrini et al., 1998; Salama, 2000; Wood, 2006).

Erosion corrosion of carbon steel in CO_2 environments involves the synergistic action of metal loss due to impingement and corrosion of an active surface. In the presence of suspended solids, the erosion

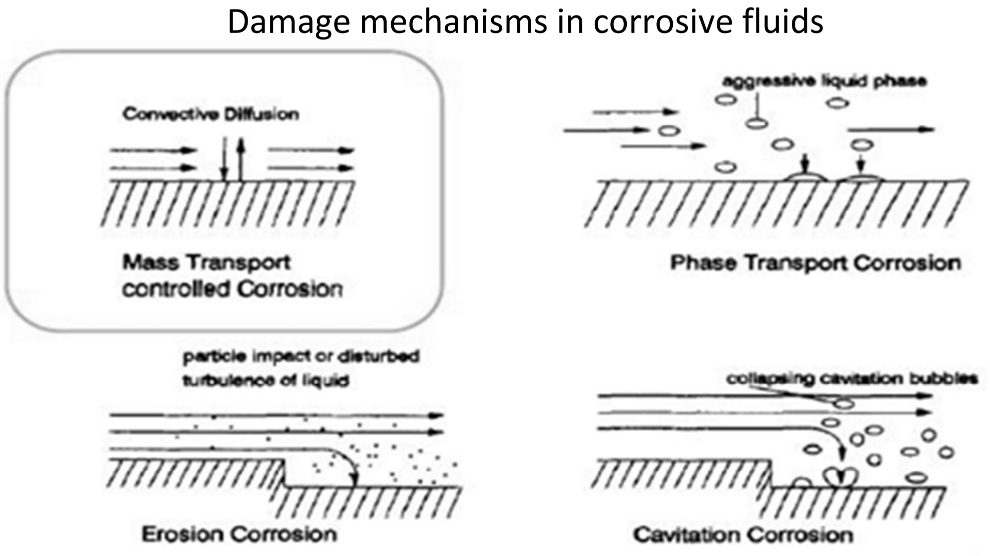

Fig. 1: The effect of flow on CO_2 corrosion (Heitz, 1996)

corrosion rate can increase by 25 – 100 times greater than the uniform corrosion rate (Ramachandra et al., 2005; Neville and Wang, 2009). Under suitable conditions $FeCO_3$ scale is the corrosion product formed in CO_2 – saturated conditions and the corrosion regimes have been determined as a function of the flow condition (French et al., 1989; Neville et al., 2003):

- $FeCO_3$ scale formation and low metal loss rates at low velocity
- Sand abrasion and removal of the scale and high metal loss rates at high velocities, and
- Partial removal of scale and localized pitting at intermediate velocities

These regimes depend on the environment and the material of construction (de Moraes et al., 2000; Neville et al., 2003).

Erosion in oil and gas production systems is mainly due to the presence of sand along with liquid and gas. Since erosion is due to mechanical forces occurring on the metal surface, erosion can be difficult to control. Erosion corrosion occurs when corrosion is accompanied by solid particle impingement (Dave et al., 2008). Erosion corrosion is defined as accelerated corrosion following the removal of surface films. It is associated with production velocities and is most severe when production velocities are high. The erosion corrosion effect is induced by rapid relative movement between a flowing electrolyte, for example, slurry and metal parts, pipes or containers. All metals can be affected to a greater or lesser degree. The presence of CO_2 in oil and gas has made the environment very corrosive and special attention must be paid to their degradation mechanism especially erosion-corrosion (Keating and Nesic, 1999; Ajeel and Ahmed, 2008; Tian and Cheng, 2008;Tandon et al., 2009).

1.6. Cost of erosion corrosion

For some decades, it has been acknowledged that erosion corrosion is the largest threat to the integrity of multiphase oil and gas pipelines. Erosion and corrosion problems in oil and gas production cost the industry hundreds of millions of dollars each year (Wood and Hutton, 1990). While GE Technologies believed that the negative effects of corrosion and erosion cost the oil and gas, and power industries billions of dollars annually, they argued that 20% to 25% of these costs could be avoided (Hedges and Bodington, 2004). It has been stated that massive costs are directed annually to alleviate corrosion and erosion corrosion costs. The cost impact of corrosion to the USA economy totalled nearly $300 billion annually and it has been suggested that erosion corrosion is about 30% of the total corrosion form (Novak and Macenauer, 1993). Erosion corrosion problems provide significant health, safety and environmental risks to the oil and gas industry due to unexpected material failure, unscheduled plant or pipeline shutdowns, inefficient or lost production, and high maintenance costs or imposed fines (Wood and Hutton, 1990; Novak and Macenaeur, 1993; Hedges and Bodington, 2004; Wang et al., 2005).

1.7. Factors that affect erosion corrosion

There are several factors affecting erosion corrosion and they can be classified as flow dynamics, concentrations, geometry, environment, solid particles among others.

Erosion corrosion is often associated with areas where fluid flows are altered and there is increased turbulence, the presence or absence of solid particles, the fluid corrosiveness and so on. The relationship between erosion corrosion rates and some variables such as (geometry, fluid velocities, fluid properties, flow regime, pipe material properties, particle diameters, and densities) have been established. Also the effects of the presence of solid particle- like sand and their characteristics, such as sharpness, geometry, and hardness has been evaluated (Heitz, 1991; Shiraz et al., 2000; Neville et al., 2003; Fan et al., 2011). The presence of contaminants and corrosive species such as oxygen, water combined with salts containing chloride, bicarbonate and sulphate accelerates erosion corrosion (Tian and Cheng, 2008; Mohammed, 2010). Table 1 listed some of the important variables related to slurry erosion (Wood et al., 2004).

Unlike erosion in sand free systems where erosion rate is related to two parameters, it was observed that the degree of damage associated with erosion corrosion in the presence of sand is a function of the following (Stack and Paungwiwat, 2002; Salama, 2000):

- Fluid characteristics: flow rate, composition, density, viscosity
- Sand characteristics: concentration, impact velocity, impact angle, number of particles hitting the surface, shape, sharpness, hardness, size distribution and density
- Component geometry: bend, tee, choke, joint
- Material properties: hardness, microstructure
- Environment: pH, electrochemical potential, chemical composition, temperature and pressure.

Table 1: Some of the main variables which influence erosion (Wood et al., 2004)

Slurry Variables	Component Variables
Liquid; viscosity, density, surface activity, lubricity, corrosivity, temperature	Bulk properties; ductility or brittleness, hardness and toughness, melting point, microstructure, shape and roughness
Particle; brittleness, size, density, relative velocity, shape, relative hardness concentration, particle/particle interaction	Surface properties; work hardening, corrosion layers, surface treatments, coating type, coating bond, microstructure
Flow field; angle of impingement, particle impact, efficiency, boundary layer, particle rebound, degradation, particle drop – out, turbulence intensity	Service variables; contacting materials, pressure, velocity, temperature, surface finish, lubrication, corrosion, hydraulic design, intermittent slurry flows

2. MECHANISM OF EROSION CORROSION

There are a number of mechanisms to describe the conjoint action of flow and corrosion that result in four types of flow-induced corrosion, viz: - mass transport controlled corrosion, phase transport controlled corrosion, erosion corrosion and cavitation corrosion (Heitz, 1991). Erosion corrosion is characterized by the combined action of flow-induced mechanical forces and electrochemical processes. The mechanical action is comprised of the following types:-

- Shear stress and pressure variations by high flow velocities mainly in disturbed flow
- Particle impact in multiphase flows (liquids containing solid particles and gas bubbles)

The interaction between erosion and corrosion is complex. In the absence of sand, corrosion is a major concern for the integrity of pipelines while the presence of sand may result in erosion, erosion-influenced corrosion (EIC), corrosion-influenced erosion (CIE), sand settling, corrosion under sand beds (underdeposit corrosion), and loss of inhibitor effectiveness. Both corrosion and erosion are essentially surface-dependent degradation related to microstructure and composition of only the near-surface region (Wood and Speyer, 2004; Wood et al., 2004).

It was pointed out that increasing flow velocities generally augments corrosion rates but they also have beneficial effects. It may enhance passivation and inhibition in such a way as to improve the transport of the passivator and inhibitor to the phase boundary (Heitz, 1991; Chen et al., 2003). In this work, the mechanisms considered are as follows: erosion, corrosion, erosion-corrosion and the underlying principle of synergism associated with erosion-corrosion.

2.1. Mechanisms of Erosion

In erosion the significant factor that defines the mechanism is the flow velocity of the fluid. At low velocity there is scale formation and low corrosion rates, while for high erosivity there is uniform corrosion which occurs at high rates and for intermediate velocity, pitting is most often observed and the penetration rates can be extremely high. The material wastage associated with erosion is called wear and it is caused by three major mechanisms: chemical dissolution of the pipe, mechanical erosion caused by fluid flow and impingement of particles on the pipe wall (Cardoso Filho and Orazem, 2001; Papavinasam and Revie, 2004).

2.2. Mechanisms of Corrosion

Corrosion mechanism is well understood and documented but in this work, we are considering CO_2 erosion corrosion in the oil and gas industry. It must be noted that the CO_2 corrosion principle is still under intensive investigation. CO_2 is found to cause an enhanced rate of general corrosion and localized corrosion and the kind of corrosion caused by dissolved CO_2 varies considerably according to the precise environmental conditions. In addition, CO_2 associates to give carbonic acid and can then dissociate further into bicarbonate and carbonate anions. These mechanisms are influenced by the resulting acidic pH. The buffering action of this carbon–containing species may also play an important role. The mechanism of the effects of dissolved CO_2 on the corrosion of steel has been successfully resolved and established (Ikeda et al., 1984; de Waard et al., 1991).

Although there is some debate about the mechanism of CO_2 corrosion in terms of which dissolved species are involved in the corrosion reaction. There is a consensus that iron carbonate is the main corrosion product and that formation (dissolution) depends on various environmental and fluid parameters. It is clear that irrespective of the exact mechanisms involved, the formation of iron carbonate films is a major controlling factor that influences the final corrosion rates observed. It is generally accepted that the CO_2 partial pressure and temperature influence the corrosion rate. Velocity effects are also very important in the CO_2 system such that turbulence is often a critical factor in pushing a sweet system into a corrosive regime. Notwithstanding this, the mechanisms of CO_2 corrosion are complicated and are influenced by many factors (Ikeda et al., 1984; de Waard et al., 1991; Gulbrandsen, 2005). The erosion corrosion of carbon steel in CO_2 environments involves the synergistic action of metal loss due to impingement and corrosion of an active surface (Cabrini et al., 1998).

2.3. Mechanisms of Erosion-Corrosion

Erosion-corrosion is a complex mechanism of material degradation resulting from interactions between electrochemical corrosion and mechanical erosion processes. The mechanism of this form of material damage is very complex due to the interaction between erosion and corrosion, and the overall damage is higher than the summation of pure erosion and corrosion. Erosion corrosion was regarded as a form of material degradation by simultaneous attack of erosion plus corrosion. It is clear that the mass loss rate by combined erosion corrosion is not simply the sum of erosion and corrosion mass loss rates. Instead, of this some synergistic effects can occur. Corrosion is often assumed to be controlled by mass transfer while erosion is controlled by the flow of a second particulate (Kang et al., 2003; Hu and Neville, 2005; Wang et al., 2005; Aracic et al., 2010; Mori et al., 2010).

Erosion-corrosion that produces the maximum impact originates from two sources. The first is the mechanical source and this is the result of high velocity of the corrosive medium (gas-oil-water emulsion) which produces cavitation and impingement. The other is electrochemical and is as a result of chemical reaction between the medium and the exposed parts. Erosion corrosion produces weight loss as a result of removal of large parts of clear-cut metal portions due to impingement and cavitation (Neville and Dougal, 2002).

The mass loss can therefore be caused by several mechanisms which can either be flow and/or impingement of suspended particles on the pipe wall and electrochemical corrosion enhanced erosion or vice versa (Birks et al., 1993; Neville et al., 2003). Substantial progress has been made towards understanding the mechanisms of erosion-corrosion of pure metals and specific alloys in particular the role of oxygen formation and its removal. Though the interaction between erosion and corrosion processes is complex, it can be rationalized into a series of regimes with a smooth transition from one regime to the next as the relative intensity of one process is varied with respect to the other (Stack et al., 2007). The modes of erosion-corrosion are diverse and may vary from being "erosion-dominated", where erosion of metal is the dominant process, to "corrosion-dominated", where erosion of oxide scale is the dominant process. The intermediate situation in which erosion of transient oxygen is the predominant process is termed "erosion-corrosion dominated" and describes the regime in which continual formation and removal of oxygen occurs down to the scale/metal interface (Malka et al., 2006).

2.4. Synergism of Erosion-Corrosion

Erosion and corrosion have a synergistic effect on each other, and as a result, the two are often grouped together as one phenomenon. Although the problem associated with this interaction is enormous, the mechanism of synergism is still not thoroughly understood because of its complexity (Papavinasam and Revie, 2004; Dave et al., 2008). It is extremely difficult to clearly separate the damage due to erosion and corrosion and this may be due to the fact that most of the work done on erosion corrosion is on a laboratory scale which is different from field work. Despite the extensive work in the past there has been no clear understanding of erosion corrosion synergistic effect on each interaction under realistic flow conditions (Wood and Hutton, 1990; Stack and Paungwiwat, 2002; Stack et al., 2006).

Synergism can be defined as the difference between erosion-corrosion and the sum of its two parts and can be expressed by the following relationships (de Waard et al., 1991):

$$T = E + C + S \qquad (1)$$

$$S = T - (E + S) \qquad (2)$$

where
T is the material loss due to erosion corrosion,
E is the material loss by pure mechanical erosion process,
C is the material loss by electrochemical corrosion processes, and
S is the combined interaction between corrosion and erosion processes.

In addition the synergistic term can further be divided into two additional components, ΔE and ΔC, where:

ΔC is the corrosion enhanced erosion, and

ΔE is the erosion-corrosion

such that

$$S = \Delta E + \Delta C \qquad (3)$$

The synergistic effects during erosion-corrosion processes may be influenced by changes in hardness induced by the surface damage, during slurry jet impingement tests. Synergism can be evaluated by using an experimental programme which includes three types of test:

- Pure erosion tests to determine the erosive wear rate
- Pure corrosion tests to determine the corrosive wear rate, and
- Combined tests to determine the total wear rate when conditions in both tests 1 and test 2 are acting

Several mechanisms have been proposed and it was reported that the magnification of the wear rate by synergism is due to fresh surfaces being created during erosion which are not immediately passivated by corrosion products and are therefore allowed to corrode at an accelerated rate (Wood and Hutton, 1990). Also it was stated that the most significant damage process was determined to be the synergistic effect and this is as a result of property degradation due to corrosion processes translated to mean that the resistance to erosion on the surface is reduced (Hu and Neville, 2009).

3. MONITORING OF EROSION CORROSION

It is well known that corrosion tests are very difficult to replicate and also that there are many factors which affect these measurements. Some of these factors include surface/sample preparation and the environment like flow velocity, pH, temperature, concentration of corrosive species and others. It is also assumed that reproducibility of these tests in various laboratories differ between 55 – 75% (Groysman and Shvarts, 2006; Papavinasam et al., 2002). Erosion corrosion may occur in the presence or absence of sand but generally it is believed that sand is present. Also it is argued that due to economic and technical reasons, new sources of energy are being developed and as such oil sands will increasingly be relied upon to make the difference in future global oil production. The quantity of sand produced in a well is regarded as unknown and as such there is a need to evaluate the sand that is produced. This can be achieved by using sand monitors and/or erosion or corrosion monitors (Shirazi et al., 2000; Tian and Cheng, 2008).

Electrochemical methods are used in the field and laboratories to measure corrosion and erosion corrosion rates. Some of the techniques include weight loss, Linear Polarization Resistance (LPR), Electrochemical Impedance Spectroscopy (EIS), Electrochemical Noise (EN), and externally monitored hydrogen permeation foils. The use of LPR to investigate erosion-corrosion has been established and it has been able to identify the conditions quickly for which erosion-corrosion may be a serious threat (Papavinasam et al., 2002; Groysman and Shvarts, 2006; Hu and Neville, 2009). In conjunction with the electrochemical techniques, there are many devices that are used for erosion-corrosion studies out of which three kinds of test techniques are extensively used. These tests are used in the laboratory to simulate the hydrodynamic conditions exerted on the materials experiencing erosion-corrosion, viz; Rotating Disk Electrode (RDE), Rotating Cylinder Electrode (RCE), and Submerged Impingement Jet system (SIJ) (Tian and Cheng, 2008).

A study discussed all three major methods of measuring flow induced corrosion critically and outlined their benefits and shortcomings. They considered jet impingement as a powerful tool that is suitable for investigating susceptibilities of materials to flow induced localized corrosion under severe flow intensities and to study the efficiency of chemical mitigation of these problems. While the rotated cylinder has the advantage that the complete flow regime from laminar to turbulent can be tested in the same arrangement. They stated that the rotated disc is preferred when studying the flow effects under laminar flow conditions, because this flow regime exists at rotated discs up to high angular velocities. Also, rotated disc is considered for investigating the mass transport phenomena because there is a direct relationship between the mass transport rate and angular velocity. They now concluded that there is a distinct differentiation between corrosion experiments and electrochemical measurements, because the limited depth of information obtained from flow influenced electrochemical measurements is often underestimated and sometimes even ignored (Schmitt and Bakalli, 2006). However, another study demonstrated the correlation of steel corrosion in pipe flow with jet impingement and rotating cylinder tests. The flow field established for a circular jet impinging on a flat plate with the jet central axis normal to the plate is as shown in Figure 2. Based on the results obtained it can be concluded that submerged impinging jet and rotating cylinder electrode laboratory test methodologies give the optimum field conditions (Effird, 2000).

Laboratory – tests for inhibitor evaluation consist of two main components – laboratory methodology and measurement technique. The combinations of laboratory methodology and measurement technique for inhibitor evaluation for multiphase systems are presented in Table 2 (ASTM G170 – 01a (2001). The features of different flow systems and related experimental tools applied in flow – related corrosion research and protection are listed in Tables 3 - 5 with respect to the flow intensity typically achieved the availability of equations for quantitative and predictive evaluation of experimental data, and whether this tool is better applied in the laboratory or in the field (Effird, 2000).

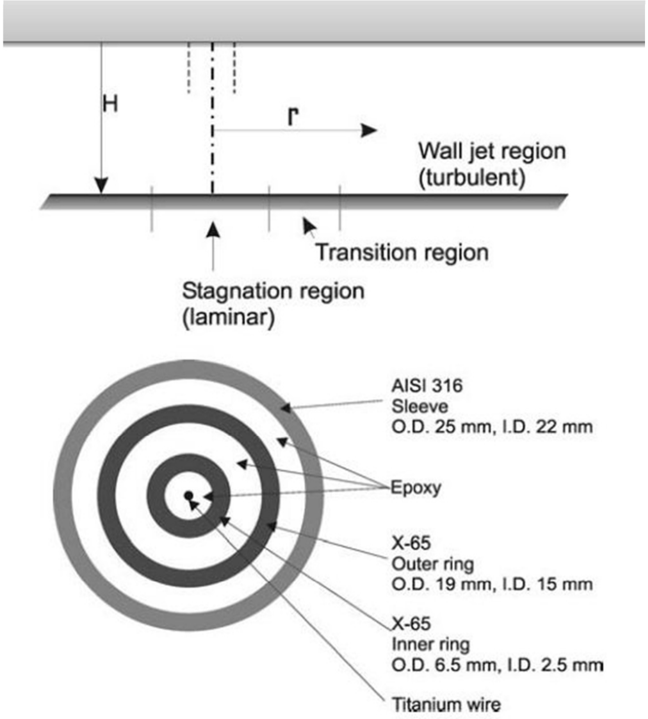

Figure 2: Hydrodynamic characteristics of jet impingement on a flat sample showing the three characteristic flow (Cabrini et al., 1997)

Table 2: Laboratory Methodologies and Measurement Techniques for Corrosion Inhibitor Evaluation (Nesic et al., 2004)

Laboratory Methodology	Measurement Techniques	Aqueous/Oil/Gas Phase	Remarks
RCE	Mass loss, electrochemical	Aqueous Phase	Specimen is cylinder
RCE	Mass loss	Aqueous/Oil Phase	Specimen is cylinder
JI	Mass loss, electrochemical	Aqueous Phase	Specimen is disc
JI	Mass loss, electrochemical	Aqueous/Oil Phase	Specimen is disc
JI	Mass loss, electrochemical	Aqueous Phase	Specimen is ring
RC	Mass loss	Aqueous or aqueous/Oil Phase	Electrochemical measurements cannot be carried out

Table 3: Remarks of Different Flow Regimes (Fan et al., 2011)

Flow System	Flow Velocity or Reynolds Number	Evaluation	Application
Simple stirred	Small	Qualitative	Laboratory
Rotated disc			
Free	Moderate	Quantitative (Levich Equation)	Laboratory
In front of wall	High	Quantitative (empirical)	Laboratory
Rotated disc			
Free	Moderate	Quantitative	Laboratory
Coaxial	High	(empirical)	
Rotated Cage	High	Quantitative (empirical)	Laboratory
Channel flow	High	Quantitative (empirical)	Laboratory, Plant
Tube flow	High	Quantitative (empirical)	Laboratory, Plant
Jet Impingement	High	Quantitative (empirical)	Laboratory

Generally, RDE and RCE are used to investigate the effects of hydrodynamic conditions of fluids on corrosion and erosion-corrosion of metals, while the impingement jet system is suitable for studying mechanical impingement of solid particles. They are also used to generate laminar and turbulent flows, respectively. When the rotating speed is sufficiently high, RDE could also generate transition and relatively turbulent flows. Devices such as slurry pots, rotating cage, slurry drum and coriolis tester can also be used for erosion-corrosion research (Schmitt and Bakalli, 2006).

4. MODELLING OF EROSION CORROSION

Generally, modelling is useful to help understand the mechanisms of degradation, predict the damage level, failure mode and the most likely location of corrosion in the oil and gas industry. These predictions can help support the development of practical guidelines to assist the pipeline industry in mitigating existing, or preventing future corrosion failures (Ryborg, 2002). The majority of erosion corrosion research has been undertaken using experimental methods. Nowadays the trend has moved towards utilization of modelling techniques which provide an additional tool for investigation. The models differ considerably in how they predict the effect of protective corrosion films and the effect of oil wetting on CO_2 corrosion, these two factors account for the most pronounced differences between the various models (Cabrini et al., 1997; Nesic et al., 2004).

4.1. Modelling of CO_2 Corrosion

There are many varieties of prediction models for CO_2 corrosion of carbon steel. Most of these models are semi-empirical, or even fully empirical with only a handful of the more recent models being based on mechanistic descriptions of the processes underlying CO_2 corrosion. The modern history of CO_2 corrosion prediction started in 1975 with the introduction of de Waard and Milliams model. The model combined the effect of CO_2 partial pressure and temperature on the corrosion rate. Over the years new approaches to CO_2 corrosion prediction and models were introduced (NORSOK, 1998; Nyborg et al., 2000).

Nyborg (2002) highlighted the advantages and limitations of models that are being used currently for CO_2 corrosion. He categorized these models into academic based organizations and industry driven, some of the former were Tulsa, Ohio, ULL, Dream among others and the former were HydroCor, NORSOK, Dream, Corpos and so on. He stated that the major factors in CO_2 corrosion are pH, protective films, oil wetting, presence or absence of H_2S, top-of-line corrosion and fluid dynamic parameters. In this work, the latter parameter is our area of interest and it must be noted that, theoretically, CO_2 corrosion is dependent on the flow velocity and these models have varying degrees of flow dependence. One of the shortcomings of these models is that they have simplified fluid flow calculation and only a few of them have a version that incorporates fluid flow. These models assumed that there is a tendency to over-emphasize the effects of flow parameters on CO_2 corrosion, however during the past decade several workers have established the importance of hydrodynamic factors in CO_2 corrosion in the oil and gas industry (Crolet and Boris, 1991; Cabrini et al., 1997; Cabrini et al., 1998; Nyborg et al., 2000).

Table 4: Mass Transport Relationship for Important Flow Regimes (Fan et al., 2011)

Flow System	Power $Sh = a.Sc^b.Re^c$	Interval of validity	Characteristic length and Reynolds Number
Free rotated disc			$L = r$,
Laminar flow	$0.60.Sc^{1/3}.Re^{1/2}$	$10^2 < Re < 10^5$	$Re = (\omega.r^2)/v$
Turbulent flow	$0.11.Sc^{1/3}.Re^{0.87}$	$Re > 10^6$	
Rotated disc in front of wall			$L = r$,
Laminar flow	$17.3.Sc^{1/3}.Re^{0.34}$	$9.10^4 < Re < 6.10^5$	$Re = (\omega.r^2)/v$
Turbulent flow	$0.50.Sc^{1/3}.Re^{0.78}$	$Re > 6.10^5$	
Free rotated cylinder			$L = r$,
Turbulent flow	$0.079.Sc^{0.35}.Re^{0.7}$	$10^2 < Re < 4\,.\,10^5$	$Re = (\omega.r^2)/v$
Coaxial cylinder	$0.0027.Sc^{1/3}.Re$	$Re < 2.7.\,10^5$	
Flat plate in channel and tube flow			$L = d_e$,
Laminar flow	$2.54.Sc^{1/3}.Re.(d_e/l)^{1/3}$	$Re < 2300$	$Re = (d_e.u)/v$
Turbulent flow	$0.079.Sc^{0.35}.Re^{0.7}$	$Re < 2300$	d_e = (4.cross section area)/perimeter
Flat plate in free area (Laminar flow)	$0.34.Sc^{1/3}.Re^{1/2}$	$Re < 5.10^5$	$L = 1$, $Re = (l.u)/v$
Rotated cage (Turbulent)	N/A	N/A	$Re_{RC} = [\omega.(r_{RC})^2]/v$
Impinging Jet			$L = d$,
Region A (Laminar)	$Sh = 1.51.Re^{0.5}.Sc^{0.33}.(H/d)^{-0.054}$	$Re < 2000$	$Re = (d.u)/v$
Region B (Transition)	$Sh = 1.12.Re^{0.5}.Sc^{0.33}.(H/d)^{-0.054}$	$4000 < Re < 16000$	d: nozzle diameter
Region C (Wall-jet)	$Sh = 1.51.Re^{0.5}.Sc^{0.33}.(H/d)^{-0.054}$		u: flow velocity in nozzle

Table 5: Wall Shear Stress and Limiting Current Density Equations used in Different Experimental Setups for Investigations on Flow Influenced Corrosion (Papavinasam et al., 2002)

Experimental Tool	Methods used		Wall Shear Stress	Limiting Current Density
	Mass loss	Electro-chemical		
Rotated Disk	+	+	$\tau_w = 6.302.\upsilon.\rho.\omega.(Re)^{1/2}$	$j_D = 0.6205.n.F.D^{0.66}.\upsilon^{-0.167}.\omega^{0.5}.C_{bulk}$
Rotated Cylinder	+	+	$\tau_w = 0.0791.\rho.(r_c)^2.\omega^{2.3}.(Re_c)^{-0.3}$	$j_D = 0.0791.n.F..C_{bulk}.(\omega/r)^{0.7}.(r/\upsilon)^{-0.3}.(\upsilon/D)^{-0.644}$
Rotated Cage	+	+	$\tau_w = 0.0791.\rho.(r_{RC})^2.\omega^{2.3}.(Re_{RC})^{-0.3}$	$j_D = k.\tau$, Leveque equation at microelectrodes under stationary condition
Flow Loop	+	+	$\tau_w = (\Delta P/\Delta L).(d/4)$	Tube: $j_D = 0.320.n.F.D^{2/3}.\upsilon^{-1/6}.I^{-1/3}r^{-1/3}.u^{0.33}.C_{bulk}$, l,r is the tube electrode length and diameter respectively Channel: $j_D = 0.81.n.F.D^{2/3}.\upsilon^{-1/6}.u^{1/2}.C_{bulk}$
Impinging Jet	+	+	$\tau_w = 0.0447.\rho U_o.(Re)^{-0.182}.(x/d)^{-2}$	$j_D = k.n.F.D^{2/3}.\upsilon^{1/6}.(0.637.u/r)^{1/2}.C_{bulk}$, r is the electrode radius $j_D = k.\tau$, Leveque equation, stationary condition

4.2. Modelling of Erosion Corrosion

It is assumed that the corrosion factors in erosion models have been generally overlooked and as such, there are no integrated erosion-corrosion models (Gulbradsen, 2005). It is observed that the estimation of corrosion rate in a multiphase system is complex due to the high number of parameters involved. The advent of the computer has expanded the horizon of the inputs that can be processed, such that what was considered unfeasible some years back can now be solved within a short time. The correlation between model output and the field experience is not satisfactory and it is still a problem (Dugstad, 1997; Stack, 2002).

One significant parameter in erosion corrosion is the velocity of the impacting particles and the general form of the equation that relates erosion to velocity and it is given as:

$$\varepsilon = k.\, V^n f(\theta) \tag{4}$$

where, ε is the erosion rate; k is a constant and is a function of particles and targets, V is the velocity; n is the velocity exponent and θ is the impact angle in degrees.

It was concluded that there is a wide variation of velocity exponents derived for different erosion-corrosion conditions, which reflects the differences in erosion resistance of the scale formed between impacts (Groysman and Shvarts, 2006). There is a need to explain the contribution of erosion maps to the development of erosion-corrosion modelling techniques in general and emphasize the role these maps play in understanding some of the obscure principles in erosion corrosion.

Erosion maps are one of the basic results obtained by using modelling and it is regarded as one of the few design guides for erosion corrosion. They are engineering maps that have been used to describe erosion corrosion interactions at elevated temperatures. A mathematical model has been developed to construct the boundaries of such maps and to predict wastage rates. The material loss is dependent on a wide range of variables such as the impacting particle properties, the target material and the environment. Erosion corrosion maps are often used to give a visual representation of these interactions and to isolate regimes in terms of flow parameters, which are “erosion-dominated” or “corrosion-dominated”. The interactions between the basic processes of erosion and corrosion is complex, but can be rationalized into a series of regimes with a smooth transition from one regime to the next as the relative intensity of one process is varied with respect to the other (Birks et al., 1993; Stack et al., 1997; Neville and Hu, 2001; Stack and Paungwiwat, 2002; Bousser et al., 2008).

It must be stated that erosion-corrosion modelling has greatly enriched the understanding of the mechanism, measurement techniques and ultimately the prevention and control methods of erosion-corrosion.

5. PREVENTION AND CONTROL

Erosion corrosion is a surface phenomenon and there are a wide variety of surface modification techniques by which we can improve the corrosion or tribological properties. There are various ways of controlling erosion-corrosion (Heitz, 1991; Chen et al., 2003; Wood and Speyer, 2004), these include cathodic protection, materials selection, design, coating, inhibitors among others. Several workers have used highly erosion-resistant ceramic coatings such as TiN, CrN but they found that these ceramic materials are brittle and ultimately fail leading to catastrophe. They are very expensive and are used in critical applications, however, the used of novel metallic coatings is still under investigation (Wood and Hutton, 1990; Stack, 2002).

It is also suggested that at the design stage, flow barriers such as blind tees, sharp corners and others should be removed (Birks et al., 1993) and the use of cathodic protection has been proposed as a viable option to reduce materials wastage significantly (Reyes and Neville, 2001). Industrially, two mitigation strategies are usually deployed and they are proper materials selection and inhibitors.

5.1. Materials Selection

Selection of materials capable of withstanding sand erosion is one of the major problems encountered in the oil and gas industry and low carbon steel is the material of construction. This is attributed to many factors but technically, mild steel can be improved with the aid of heat treatment and alloying.

Materials selection for erosion-corrosion is based on the use of corrosion resistant alloys, coatings which include hard-metals, cermets and ceramics. Since it is a surface phenomenon, surface degradation control techniques other than surface selection may well include the use of inhibitors as well as controlling fluid temperature, pH and dissolved oxygen. Cost considerations are one of the major factors in selecting coating materials. Cheap organic coatings tend to perform relatively poorly under high energy solid particle impingement but have a use as corrosion barrier coatings within low energy flow components. The use of ceramic coatings is limited to critical applications because they are usually expensive. Importantly in order to achieve a long-term corrosion resistance, it is important to understand the consequence of selecting anodic and cathodic coatings relative to their substrate. It was concluded that materials selection for tribocorrosion systems is extremely challenging and is based on optimising performance against the combined degradation processes. A wide range of corrosion resistant materials relies on a relatively thin surface film to provide a barrier (of high impedance) to charge transfer (and thus corrosion) between the relatively active bulk material and the corrosive environment (Stack et al., 1997).

In severe operating conditions such as erosion-corrosion conditions, corrosion resistance alloys are commonly used but generally they do not resist erosion very well. Materials selection for oil and gas production can be summarized as (Wood and Hutton, 1990; Wang et al., 2005; Schmitt and Bakalli, 2006; Tian and Cheng, 2008; Neville and Wang, 2009; Aracic et al., 2010):

- Use of carbon steels with suitable chemical inhibitors
- Use of corrosion resistant alloys (CRAs) without adding corrosion inhibitors, and
- Mixed compilations where the upper part is carbon steel with inhibitor and the lower part is made of corrosion resistant alloys.

5.2. Inhibitors

Inhibitor action may involve both the reduction of metal loss during impingement and subsequent retardation of active corrosion. It is well known that carbon and low alloy steels suffer metal loss via a synergistic erosion-corrosion mechanism in corrosive solids-containing environments. Also, that corrosion inhibiting chemicals are frequently used to mitigate the corrosion component in hydrocarbon systems. Achieving effective corrosion inhibition in high velocity systems suffering from erosion-corrosion has historically been considered difficult (Stack et al., 1997).

It has been established that chemical inhibitors must be able to recognize the corrosion agents present in the system such as chloride, oxide, carbonate and others (Stack et al., 2006; Dave et al., 2008; Neville and Wang, 2009). Corrosion inhibitor prevents attack by formation of a film on the metal surface as illustrates in Figure 3. The inhibitor may interfere with either the anodic or cathodic reaction. Also the efficiency of corrosion inhibitors in flowing media depends on local flow intensities. Above critical flow intensities inhibitors lose their efficiency as shown in Figure 4a. While in Figure 4b the critical flow intensities initiation can also depend on the inhibitor concentration which depends on the chemical structure of the active inhibitor compounds and the formulation of inhibitor packages in erosion-corrosion. It has been demonstrated that inhibitor performance is a function of the type of inhibitor at a particular concentration and flow intensity (Schmitt et al., 1990; Wang, 2007).

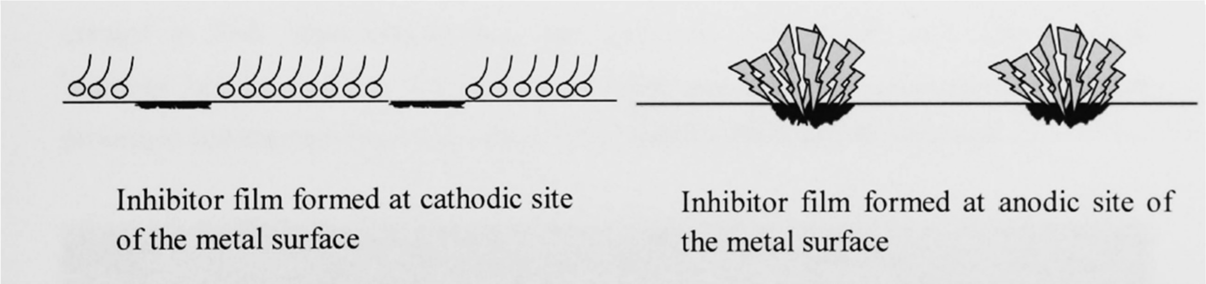

Figure 3: Corrosion inhibitor preventing attack by formation of a barrier on the metal surface (Wang, 2007).

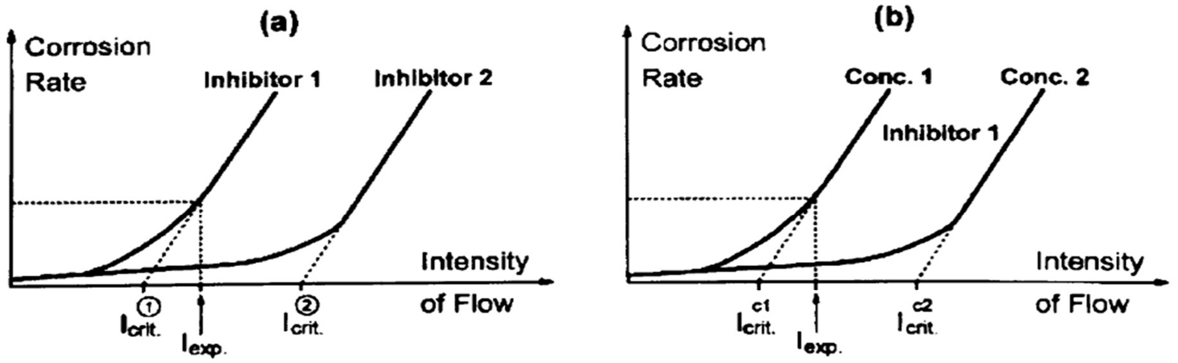

Figure 4: Effect of flow intensity on corrosion inhibitor performance (Schmitt, 2001)

Organic, adsorption-type corrosion inhibitors are used in the oil and gas industry generally and they act on the metal surface. This phenomenon is strongly dependent on the nature and surface charge of the metal, the type of aggressive electrolyte and the chemical structure of the inhibitor. The most important prerequisite for compounds to be efficient inhibitors under erosion/corrosion conditions is that they should chemisorb on the metal surface forming a barrier layer (de Damborenea et al., 1997; Durnie et al., 2001).

6. CONCLUSIONS

This paper has highlighted the several studies on erosion corrosion and the general mechanisms have been established. The mechanisms are regarded as being driven by synergistic effects of both erosion and corrosion. The degradation is a surface phenomena and this makes application of surface engineering to be an ideal procedure for its prevention and control. In the oil and gas industry, materials selection, coatings and inhibitors are the most common choices of prevention and control. It is believed that the former is more critical to the success of the prevention strategies. It is apparent that the general mechanism is well understood but some areas are still under consideration such as the fluid dynamics and the utilization of inhibitors. Hence concerted efforts need to be deployed in evaluation of the effect of the hydrodynamics and inhibitors characteristics.

ACKNOWLEDGEMENTS

We will like to thank the following organizations for their financial assistance: ETF, NIGERIA; NASENI, NIGERIA; Carnegie Corporation through OAU Linkages, NIGERIA and School of Mechanical Engineering, University of Leeds, UK.

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